

Nanotechnology methods and creation of the terabit storage

V. A. Bykov, A. V. Emelyanov, E. A. Poltoratski and V. N. Riabokon

State Research Center Zelenograd State Research Physical Problem Institute,
Zelenograd, Moscow, 103460, Russia

A special direction of research in the field of nanoelectronic devices is creation of storage devices having superhigh density and terabit capacity (terabit storage). The idea that such storage devices can be created appeared soon after STM capable of manipulating separate atoms had been developed — in the US the corresponding patent was granted in 1986. A wide diversity of ways to form local nonuniformities on a great variety of surfaces have been tried, to the point of carrying atoms from place to place and making inscriptions and pictures of them. The most impressive achievements of this “romantic” period were the works of Eigler, Mamin, Aono. However, it became clear rather quickly that the use of STM as a reading tool imposes very stringent requirements on the storage medium. The basis of STM operation — tunnel current — exponentially depends on the probe-substrate gap estimated at several of angstroms. For this reason, recording-reading speeds at a level of 10^5 – 10^6 bits per second can only be achieved with storage elements being identical practically with atomic accuracy. This means that it is necessary to work either under conditions of superhigh vacuum or under usual conditions, but with atomically smooth and atomically ordered substrates.

To meet these requirements, the concept of using self-organizing ordered atomic-molecular structures as a storage medium was put forward, and the appropriate copyright certificate was received in the USSR in 1989 (A. V. Emelyanov, E. A. Poltoratsky, N. S. Samsonov. Read-only memory and method of writing. USSR Pat. N 1655240. Prior. 30.01.1989). Ordered structures of organosilicon compounds on graphite substrates were tested, and the possibility of recording memory elements of size 0.5 nm was demonstrated. However, the uncontrollability of the STM probe tip at the atomic level and the limited set of substrates allowing work under normal conditions gave no way of going beyond separate successful experiments. Moreover, works performed under conditions of superhigh vacuum on atomically clean surfaces have shown that carrying separate atoms from a substrate to a probe or from a probe onto a substrate is far from being so simple. These processes are of probabilistic character with characteristic times at the level of several to tens of milliseconds, so the necessity for normal storage operation recording validity at a level 10^5 – 10^6 is out of the question.

The success in development of the atomic force microscopy, and in particular, the opportunity to use micromechanical cantilevers became an essential stimulus to intensification of works on creating terabit storage. By now, impressing results concerning storage media have been obtained: equivalent recording speeds of 0.01–0.1 Mbits per second on a polymeric carrier with a micromechanical cantilever containing a built-in device for warming-up the probe tip and reading speeds of the order of 1 Mbits per second with lightweight cantilevers are possible. Some breadboard models of the terabit storage were tested, the polycarbonate polymer used for manufacturing CD and DVD is a good model of storage medium for them. As a result of the researches carried out by us with the help of AFM (Solver-P4-18RM, Solver-P47, NT MDT Co., Moscow-Zelenograd, www.ntmdt.ru), 10 kbit arrays of bit-by-bit recording (Fig. 1) with a density of 100 Gbit/cm^2 and also arrays

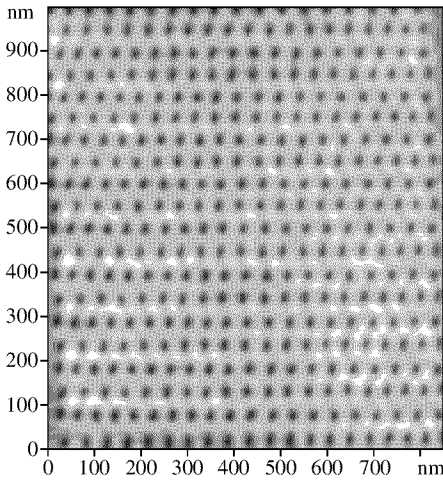


Fig. 1. Example of bit-by-bit recording.

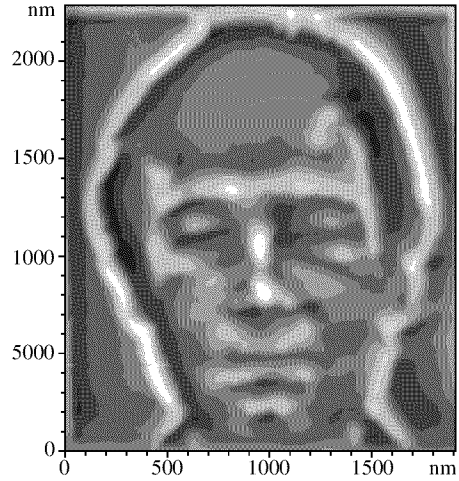


Fig. 2. Example of analog recording.

of analog image recording (Fig. 2) with an equivalent density of 800 Gbit/cm² were obtained. A complex approach is necessary for successful development of the terabit storage. This is due first of all to the interdependence of the parameters of a storage device and the micromechanical recording–reading head. A compromise should be reached on a lot of parameters, beginning with those directly associated with the functioning principle of a storage medium (recording on a relief, recording on electrical, magnetic and other nonuniformities), and also including, for example, such parameters, as mechanical properties of the material of the store (wear resistance) and cantilever (rigidity and weight).

Thus, the basic tasks in the initial stage are to develop both a storage device and a micro-electromechanical recording–reading head with corresponding characteristics, and then to elaborate technical requirements and ways for creating other elements of the terabit storage: addressing systems, store drive, electronic control units, software etc. It is necessary to note that unlike the storage device, the above units are already present to some extent in atomic force microscopes of the newest types and on CD and magnetic disks, which must ensure a certain continuity of the development of similar storage system units.

The achieved recording and reading speeds are insufficient for successful competition in a set of parameters with the storage systems developed on the basis of traditional methods. Use of multiprobe devices is a natural way to increase the productivity of a recording and reading system. Taking into account the potential opportunity to create micromechanical probe devices with hundreds, up to a thousand of probes, devices with electrical recording and reading seem to be the optimal choice because of the simplest probe design and the system of recording–reading as a whole. Storage media with electrical recording–reading on the basis of arrays of metal clusters located on a semiconductor (silicon) substrate are of interest as storage media for the terabit storage in question. Nanometer-size clusters are made of metals forming silicides rather easily upon heating to several hundred degrees. A writing current pulse warms up the interface between a metal cluster and the silicon substrate and transforms it into silicide. This changes the Schottky barrier height and can be used for subsequent reading. A prototype structure investigated by us was made on the basis of porous silicon, into whose pores a metal, Pd in particular, was electrochemically

deposited. After etching porous silicon, Pd clusters of sizes 100–200 nm remained on its surface. These clusters were used as memory elements. In experiments carried out with Pd clusters at a reverse bias of -1.5 V the current varied between 1.6 and 5.5 nA.

The proposed class of storage devices represents a micromechanical design including plane or linear array of controlled probes with tensoresistive sensitive elements. The recording and reading in such storage devices are carried out by special micromechanical multiprobe heads with a large number of controlled microprobe on disks rotated by micro-motors, or cylinders with a layer of a sensitive material specially deposited on the surface. The micromechanical multiprobe head contains very sharp probes with a radius of curvature of 1–2 nm, placed on mobile cantilevers. Such multiprobe heads (with 8 and 16 probes) are being developed by us now and used as sensor controls in atomic force microscopes. With the help of such probes, it is possible to make updating of a film structures surface similar to above mentioned. The density of probes in the multiprobe head can be as high as 100 probes per 1 mm. To enable recording with a step of up to 10 nm, a linear probe array is placed on a single-coordinate scanner (this may be a small piezoelectric table) providing parallel shift of the probe array.

Having an information storage capacity exceeding by two to three orders of magnitude that of modern storage devices based on magnetic and compact discs, comparable speeds of recording–reading and reduced mass and overall dimensional characteristics, the terabit storage devices are especially attractive for use in global (including space-borne) information networks, small spacecraft and unmanned space vehicles.

The above design of the storage device allows us to consider the storage medium based on silicon with a metallic cluster array also a basis for creating digital nanoelectronic devices. In phase transformation occurring during recording, coupling between closely spaced clusters varies together with the conductivity in the system metal cluster–substrate tunnel. This allows forming a certain system of tunnel-coupled quantum wells, which can form a basis for a computing device. This technology of creating digital nanoelectronic systems differs essentially from the traditional operating group methods of microelectronic technology, with technological parameters having some average values over the whole substrate. Thus, dispersion of the characteristics of separate nanoelements is inevitable, which gives no way of creating large computing systems. Application of micromechanical multiprobe nanolithographic heads furnishes essentially new opportunities. The action on a substrate becomes not averaged, but rather “intellectually” local. Thus, an opportunity arises to exert not simply local influence, but also to preliminarily define local parameters, to choose local technological modifications and to perform subsequent local control. Thus, it can be expected with greater confidence that large arrays of interacting nanoelements can be created with reasonable dispersion of parameters. The above-mentioned example of analog recording of images with dosed action in each point (Fig. 2) to a certain degree illustrates this approach.

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